STRUCTURAL PARAMETERS FOR GLOBULAR CLUSTERS IN M 31

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ABSTRACT: After a review of existing data on structural parameters for globular clusters, we present new measurements of tidal radii for 30 globular clusters in M 31. These measurements are consistent with the globular clusters in M 31 having the same mean M/L ratio as those in the Galaxy.

1. INTRODUCTION

The shapes of globular clusters are determined by a combination of internal dynamics and external forces such as the tidal field of the galaxy. By studying the projected spatial distribution of stars within the cluster (or the image shape, for unresolved clusters in distant extragalactic systems), one can derive constraints on the mass-to-light ratio within the cluster and the galaxy, on the tidal potential of the galaxy, and on the cluster orbital properties. We review the data on globular cluster profiles (excluding the details of the very central core) in the Galaxy, the Magellanic Clouds, and M 31. This seems a highly appropriate topic for a meeting dedicated to CCDs in astronomy, as extragalactic globular clusters are such difficult observational targets that until the advent of the CCD detector our knowledge of their properties was extremely limited. Since globular clusters are seen against a spatially varying background of light from the host galaxy, and are easily confused with foreground stars and background galaxies, the linearity, sensitivity, and large dynamic range characteristic of CCDs are crucial to recent progress in this field.

2. ELLIPTICITIES

Globular clusters are not spherical. Deviations from sphericity may arise as a result of anisotropies in the initial collapse of a cluster, from tidal effects from the host galaxy, or from internal rotation. In the Galaxy, the survey by White and Shawl (1987) has found that the mean de-projected ellipticity is 0.12 ± 0.01. In the few cases for which there are extensive high-precision radial velocity measurements of an adequate sample of stars to determine the rotation of the cluster, the ellipticity appears to be completely explained by rotation, which ranges from an upper limit of 1 km/sec in M 3 (Gunn and

A. G. Davis Philip, D. S. Hayes and S. J. Adelman (eds.)
CCDS IN ASTRONOMY. II.
167 - 176 © 1990
L. Davis Press

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Griffin 1979) to a maximum value of 8 km/sec in ω Cen (Meylan 1987).

A large sample of clusters has been studied in the Magellanic Clouds by Geisler and Hodge (1980) and Frenk and Fall (1982). The mean de-projected ellipticity for the LMC cluster sample is 0.18, definitely larger than the mean for the Galactic sample. But the Magellanic Cloud clusters sample a wide range in age as well as metallicity, and Frenk and Fall (1982) have established that the youngest clusters are the most elliptical, while the mean ellipticity of the oldest LMC clusters is comparable to that of the galactic sample. It thus appears possible that the ellipticity of the youngest LMC clusters is a residual from their initial formation, which decays with time. N-body calculations by Fall and Frenk (1984) substantiate this idea, with the ellipticity decreasing by a factor of two over a few τ_{rh}, the relaxation time at the radius containing half the total mass.

Fusi Peci (1988) reviews the work to date on the M 31 globular cluster system. These clusters are also spatially resolved, and ellipticites for a small sample are available (Spassova, Staneva and Golev 1988, Lupton 1989). They are indistinguishable in the mean from those of the galactic globular cluster system, and thus their ellipticities probably indicate internal rotation. The samples studied with sufficiently deep images taken in good seeing and carefully analyzed are quite small, and more work in this area is indicated.

3. TIDAL RADII

The boundary of a globular cluster is limited by the tidal field of the Galaxy; the tidal radius, r_t, corresponds to the inner Lagrangian point. Since globular cluster orbits are not circular, and galactic force fields are not spherically symmetric either, the actual definition of r_t is somewhat murky. Seitzer (1985) has confirmed with an N body calculation that the approximation that the tidal radius for clusters in eccentric orbits is set at perigalacticon, where the tidal force is maximum, is adequate. The tidal radius thus is given by

$$r_t = R_p \left[\frac{M_{cl}}{(3+e)M_p}\right]^{\frac{1}{3}},$$

where R_p is the perigalactic distance, M_p is the mass of the galaxy interior to R_p, and e is the eccentricity of the cluster's orbit.

In the Galaxy, since we know for each cluster the true distance from the galactic center, R_{GC}, rather than just the projected distance, we can combine this with observed radial velocities for all the clusters to derive the eccentricity of the cluster system orbits. Measurement of tidal radii for galactic globular clusters is best done by star counts and profile fitting, as was first carried out by

Peterson and King (1975), and used by Peterson (1974) to study the orbital properties of the clusters. He found that an isotropic distribution of cluster velocities is consistent with the data. Innanen, Harris and Webbink (1983) carried out a similar investigation.

The clusters in the Magellanic Clouds are well resolved, and their tidal radii can also be measured by star counts (see, for example, Kontizas, Hadjidimitriou and Kontizas 1987). But it takes several orbits for the tidal limit to impose itself, and for the youngest clusters in the Magellanic Clouds, there may not have been enough time for that to have occurred. Recent papers by Elson and collaborators (Elson, Fall and Freeman 1987 and 1989) support this idea. They have found at least one case where the cluster profile extends smoothly, following a power law of $r^{-2.5}$, beyond where one would expect the tidal radius to be located based on calculations of the mass of the cluster using mass-to-light ratios from stellar evolutionary models. The refinement of calculating the mass-to-light ratio from velocity dispersions added by Lupton, Fall, Freeman and Elson (1989) confirms this result for the cluster NGC 1866. This cluster is very young, with an age of 10^7 years, while its orbital period around the LMC is about 5×10^8 years.

Another tantalizing glimpse of possible age effects was suggested by Elson, Freeman and Lauer (1989), who claim that the size of the cores of clusters in the LMC shows a correlation with age in the sense that older clusters have more extended cores. They explain this as an expansion driven by mass loss from evolving stars.

Ken Freeman and I have measured the tidal radii of a sample of globular clusters in M 31 chosen to extend from the nucleus out along the minor axis. The clusters were picked from the survey by Sargent, Kowal and Hartwick (1977). A non-trivial fraction of the outermost clusters could not be confirmed, but rather were galaxies or small groups of foreground galactic stars. The images were taken on two nights of sub-arcsecond seeing with the Four Shooter on the 200-inch Cassegrain focus. The scale is 0.34 arc-sec/pixel. Ignoring ellipticity, the cluster radial profile was determined. Fig. 1 shows a typical profile, I_i, for a globular in M 31 compared to that of a point source. For most clusters, there were three frames of varying exposure times taken in either the g or r filter of the Thuan-Gunn (1976) system.

Finding a suitable algorithm to determine the tidal radii was not easy. One could attempt a fit of a King (1962) profile convolved with the point spread function over the entire image profile (K_i), minimizing χ^2,

$$\chi^2 = \sum \frac{(I_i - K_i)^2}{\sigma_i^2}$$

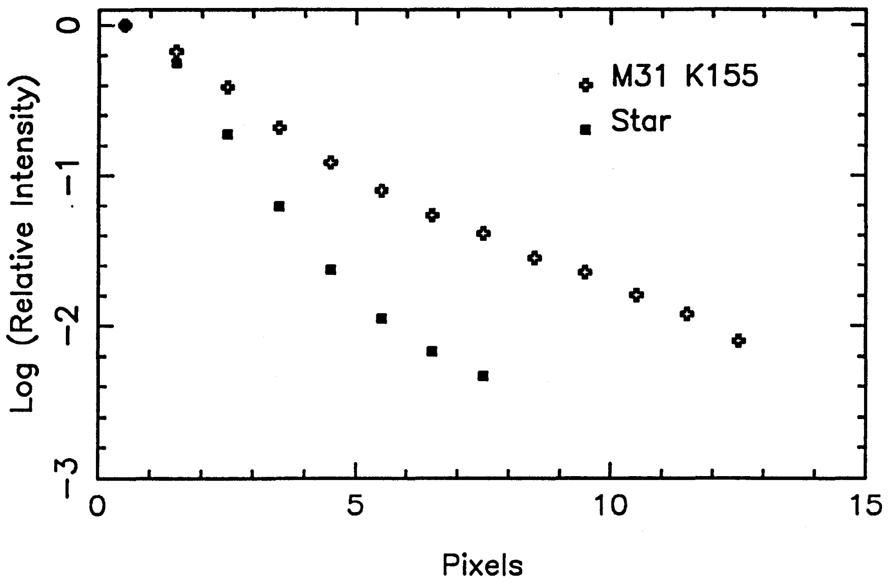

Fig. 1. The image profile as a function of pixels from the center for the globular cluster K 155 in M 31 as compared to that of a point source.

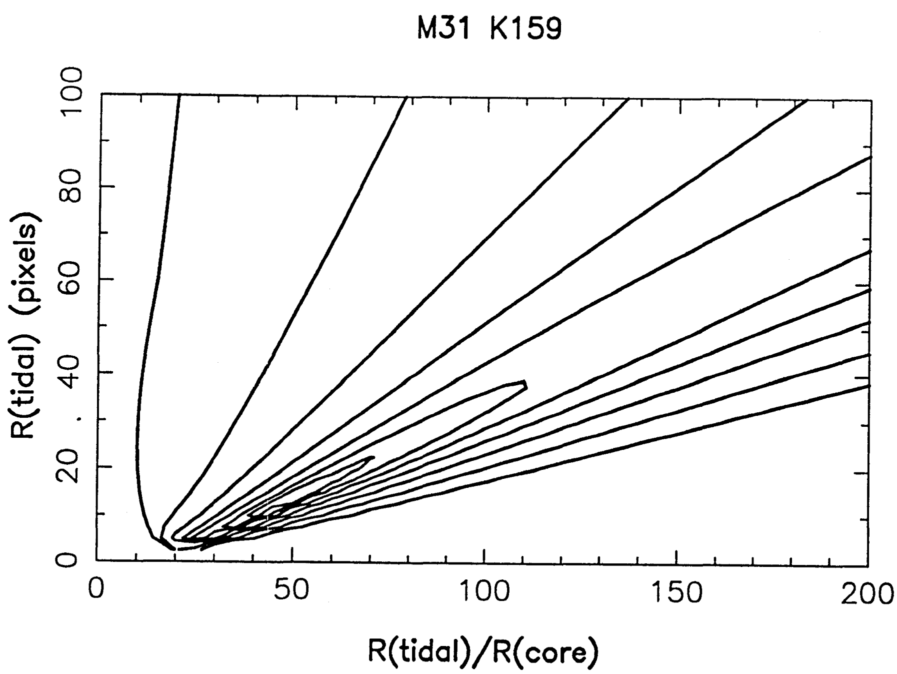

Fig. 2. Contours of constant χ^2 for fitting King profiles to the observed image profile of M 31 K 159 are shown. The contours are separated by factors of two in χ^2.

where σ_i is taken from the Poisson statistics of the detector counts/pixel. But this gives undue weight to the central pixels where small errors in the stellar point spread function have a large effect on χ^2. While such fits were attempted, they were in fact used to derive the half-light radii, r_e. Only pixels more than 1 arc-sec from the center were used to derive the tidal radius.

Ignoring ellipticity, there are two parameters to be fit, r_t and the core radius r_c; the values of r_t we obtain are listed in Table 1 for the sample of 30 globular clusters in M 31. The coupling between the two parameters is illustrated in Fig. 2, which shows the contours of a constant value of the parameter χ^2 for fitting King profiles. The contours are spaced by a factor of two in χ^2. Since the profiles don't extend out to as large a spatial extent as desirable (r = 5 arcsec at best), the tidal radii are quite uncertain, typical errors being +100%, -30%.

A plot of r_t versus the galactocentric radius R_{GC} for the M 31 and galactic globular clusters is not very illuminating. If one attempts to remove the effect of varying cluster mass, by assuming M/L = 2.0 for all globular clusters in both galaxies, one obtains Figs. 3 and 4, which show $r_t/M_{cl}^{1/3}$. Although the measured values of r_t are uncertain, particularly those in M 31, the scatter in these figures must reflect the distribution of orbital eccentricity, and in the case of M 31, projection effects. But there is considerable similarity between Fig. 3 and Fig. 4.

To attempt to quantify this apparent similarity is difficult. In M 31 we only have projected distances, and we know nothing about the orbital properties of the cluster system, beyond that the cluster system as a whole appears to be rotating (Huchra, Stauffer and Van Speybroeck 1982). We divide the sample of clusters into two radial zones, R_{GC} < 4 kpc, and those outside that point. The mean value of $r_t/M_{cl}^{1/3}$ for each zone is given in Table 2. The mean over a comparable radial range, correcting for projection effects, for galactic globular clusters with M_V < -7.1 mag from Webbink's (1985) compilation, is also given. (The cutoff in M_V applied to the galactic sample reflects the higher mean brightness of the magnitude-limited M 31 cluster sample.) The mean $r_t/M_{cl}^{1/3}$ is somewhat larger in the Galaxy for each annulus. But M 31 itself is a more luminous galaxy, and if we assume that M/L is identical as a function of position for the two galaxies, we can correct the mean galactic value appropriately to reflect the 0.6 mag integrated luminosity difference. These values are given in Table 2 as $\langle r_t/M_{cl}^{1/3}\rangle_c$. The corrected value for galactic globular clusters and $\langle r_t/M_{cl}^{1/3}\rangle$ for M 31 globular clusters agree in each annulus to within 2 %, which given the uncertainties must be coincidental.

We thus find that the tidal radii of the two samples behave as

TABLE 1

Properties of the M 31 Globular Clusters

ID	r (mag)	g - r (mag)	R_{GC} (kpc)	r_t (pc)	r_e (pc)
vdB 5			0.5	23	2.1
K 25	18.71	0.91	10.7	48	3.1
K 108	15.62	0.44	4.3	63	3.5
K 109	17.56	0.43	6.5	15	2.6
K 111	17.21	0.40	5.7	19	3.7
K 122			16.0	39	2.6
K 124	15.23	0.71	3.1	21	2.2
K 132	18.30	0.02	2.5	20	4.0
K 135	16.56	0.38	5.7	23	2.7
K 143	16.62	0.44	11.8	15	1.5
K 146	16.90	0.42	6.0	21	4.0
K 151	17.99	0.00	1.5	38	2.6
K 155	16.49	0.51	1.4	28	2.7
K 159	16.48	0.53	2.0	18	3.0
K 165			0.7	20	2.5
K 169			0.9	18	1.7
K 174			0.6	31	2.3
K 177			0.5	11	1.1
K 180			9.3	19	2.6
K 184	16.79	0.39	0.6	15	1.8
K 185			0.2	20	2.9
K 189			0.3	13	2.2
K 194	16.68	0.30	0.8	23	2.2
K 198	15.76	0.39	0.9	18	1.7
K 200			0.8	12	1.3
K 202	17.37	0.35	9.3	27	4.3
K 207	15.86	0.40	1.1	20	2.3
K 208	16.62	0.50	1.1	22	2.7
K 308	17.30	0.61	10.3	41	3.8
K 312	15.95	0.69	0.9	34	2.9

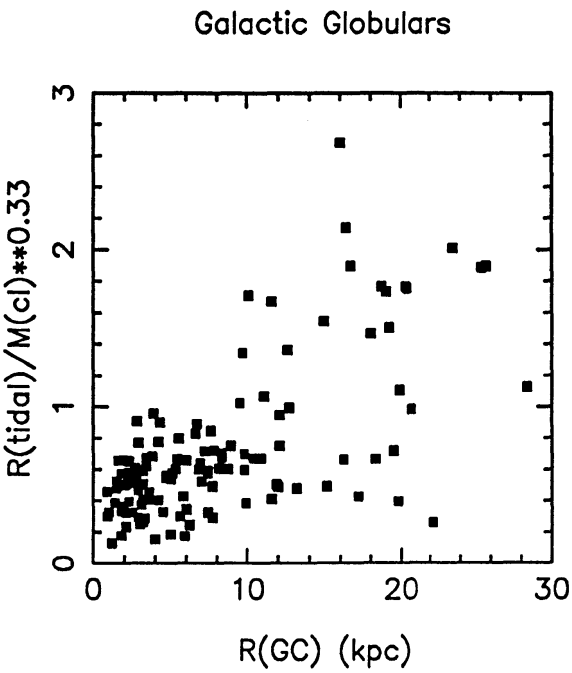

Fig. 3. The tidal radii corrected for the variation in cluster mass as a function of the galactocentric radius for the brighter galactic globular clusters.

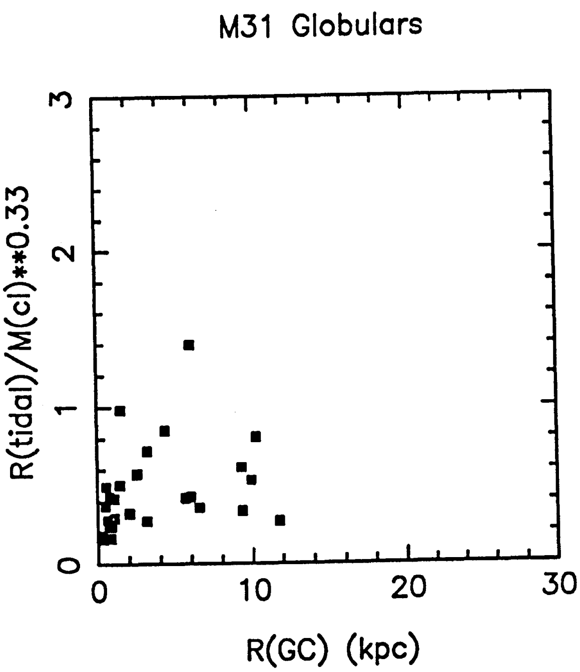

Fig. 4. The tidal radii corrected for the variation in cluster mass as a function of projected galactocentric radius for the M 31 clusters.

would be expected if the mass-to-light ratios, both within a cluster and for the galaxy itself, and the orbital eccentricity distributions are identical, to within the limits of the measurements. If one assumes isotropic velocity distributions in both cases and identical M/L ratios in the galaxies themselves, this implies that the mean M/L is identical to within a factor of two between the M 31 globular clusters and those of the Galaxy.

TABLE 2

Mean Tidal Radii Corrected for Cluster Mass

The Galaxy				M 31		
RGC (kpc)	No.	$<r_t M_{cl}^{1/3}>$ $(pc/M_o^{0.33})$	$<r_t M_{cl}^{1/3}>_c$ $(pc/M_o^{0.33})$	RGC (kpc)	No.	$<r_t M_{cl}^{1/3}>$ $(pc/M_o^{0.33})$
<4.4	26	0.45	0.37	<4	18	0.37
4.4<17.6	36	0.68	0.57	4<16	12	0.58

4. CONCLUSION

It is remarkable how alike globular cluster systems are from galaxy to galaxy (see the reviews by Harris 1987 and Harris 1988), differing only in their absolute numbers and mean metallicities. This similarity has been confirmed for yet another time by new measurements of the tidal radii of 30 globular clusters in M 31. It now appears that the globular clusters we see today are a pathetic remnant of some much larger initial population, only those that managed to survive such processes as tidal stripping, evaporation, repeated passages through the galactic disk and bulge, and dynamical friction (see, for example, Aguilar, Ostriker and Hut 1988). If that is the case, if the globular cluster systems we see today do not reflect primarily conditions at early epochs of galaxy formation (see Fall and Rees 1985 for a discussion of such theories), but rather reflect survival statistics, it is extremely interesting that these destruction mechanisms appear to operate more or less uniformly in different galaxies.

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DISCUSSION

BAGNUOLO: Where is the long tail in the distribution of globular clusters in M 31?

COHEN: The tail seen in the distribution of tidal radii for the galactic globular clusters is not seen because the M 31 sample is magnitude limited and does not include globular clusters very far out in the halo. In the Galaxy, it's the low-luminosity extremely distant globular clusters that have the largest tidal radii.